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Edward Charles Schmidt, University of ...

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ENGINEERING EXPERIMENT STATION

BULLETIN No. 11 APRIL 1907

EFFECT OF SCALE ON THE TRANSMISSION OF HEAT THROUGH LOCOMOTIVE BOILER TUBES

BY EDWARD C. SCHMIDT, M. E., ASSOCIATE PROFESSOR OF RAILWAY ENGINEERING, AND
JOHN M. SNODGRASS, B. S., INSTRUCTOR IN RAILWAY ENGINEERING

During the past twenty or thirty years there has been considerable discussion in railroad circles as to the effect of scale upon the heat-transmitting properties of tube surfaces, and the consequent effect upon the consumption of fuel. Statements as to the extent to which deposits of scale affect the conductivity of a tube or sheet have been made from time to time and have differed widely.

In a committee report on boiler incrustation in the Proceedings of the American Railway Master Mechanics Association of 1872, we find the following quotation from a paper by Dr. Joseph G. Rodgers before the American Association for the Advancement of Science, given as the best information which the committee had been able to obtain: "The evil effects of scale are due to the fact that it is relatively a non-conductor of heat. Its conducting power compared with that of iron is as 1 to 37.5. This known, it is readily appreciated that more fuel is required to heat water through scale and iron than through iron alone. It has been demonstrated that a scale $\frac{1}{16}$ in. thick requires the extra expenditure of 15% more fuel. As the scale thickens the ratio increases. Thus when it is $\frac{1}{4}$ in. thick, 60% more is required; ... ."

The report continues as follows: "On most western roads incrustations will form to a thickness of from $\frac{1}{8}$ in. to $\frac{3}{16}$ in. in the course of one year, and will increase at a still greater ratio as long as the engine is kept in service. Thus after four months' time, there will have accumulated in our engines nearly $\frac{1}{16}$ in. of scale. If Dr. Rodgers' theory be correct, after one month's service our engines will consume 3¾% more fuel than at first; after two months' service 7½% and so on, making an average for the year of over 20% more fuel than they would have consumed if using pure water."

In a report before the same Society in the year 1877 upon "Feed Water" a committee under the sub-heading, "The Effect of Incrustations on the Consumption of Fuel," reports in part as follows: "The increase in the consumption of fuel, on account of incrustations on the heating surfaces of boilers, varies with the thickness and density of the deposit. When porous the water will penetrate it, but when hard and compact it presents a complete barrier to the contact of the water with the heating surfaces. As incrustations are poor conductors of heat, an increased consumption of fuel is inevitable where they exist." The committee then cites a number of cases for which sufficient data were collected to estimate the per cent loss that was occasioned due to scale deposits. A table showing the average miles run to one ton of coal by engines upon the Illinois Central Railroad for three months prior to and for three months after the removal of incrustations, including 120 such cases and extending over a period of three years, showed as a general average an increase of 11% in the consumption of coal for three months prior to the cleaning of the boilers, as compared with the three months immediately succeeding. The result of 11% loss due to scale is, of course, entirely a general result, as individual cases often showed less miles run per ton of coal after cleaning than before. This difference from the general result could in most cases be accounted for by weather differences. A second case is cited for two passenger engines, which were of the same size and pattern, and which were run with the same trains on alternate days. Records were kept for the six months preceding and six months following the cleaning of the boilers. Both engines had previously been cleaned at the same time and had made an average of 34,047 miles before the test began. The tests as run showed a difference in favor of clean

heating surfaces of 17.5%. Mr. Wells, the master mechanic making this test, however, concludes, on account of the scaled tubes being run more often during the winter months than the cleaned tubes, that of the 17.5% difference in consumption of fuel between clean and incrusted heating surfaces about 2% was due to temperature and 15½% to the effects of incrustation. Similar tests with two freight engines gave a difference of 26% in favor of clean heating surfaces. A correction of 4% was applied to this on account of different atmospheric temperatures under which the tests were made, "thus giving a net saving of 22% in favor of clean boilers on two freight engines."

Other cases might be mentioned giving results more or less similar, also cases in which little or no loss was found to be occasioned by the presence of scale. Likewise, the opinion has been not uncommonly expressed that there is either no fuel loss due to the presence of scale in the usual amounts or that loss is so small as to be of little practical importance.

During the last few years there have been made by the Railway Engineering department of the University of Illinois four series of experiments to determine the relative conductivities for heat of clean and scale-covered locomotive boiler heating surfaces. A fifth series of tests is now being carried on along the same general lines as the others. It is the purpose of this bulletin to report upon the results of the first four series of these tests.

The tests were planned with the purpose of determining, not only the actual transmission loss due to scale in individual cases, but also the relation of this loss to the scale thickness. The last three series were arranged especially to try to determine whether there is any regularity of variation of heat transmission loss with scale thickness and to study at the same time the effects of chemical composition on this loss.

It was recognized from the outset that in any series of comparative tests for the purpose of determining the loss in heat transmission due to the presence of scale, practically exact similarity of conditions was essential for trustworthy results. A study of previous work done along this line, such as the cases and results already referred to, also served to emphasize the necessity of such care. In all of the work hereinafter reported the greatest stress has been laid upon this point, i. e. the elimination of variations in conditions except the scale itself. The difficulties

which have been encountered while prosecuting this work have still further emphasized this necessity. The difficulties attending road-testing are well understood both as to exact measurements and similarity of conditions. These considerations were of weight in determining that the tests herein reported should be largely of laboratory character rather than road tests.

The first series* of tests was made during May and June 1898. The method employed in making the tests was as follows:—

A Mogul freight locomotive, which had been in service 21 months and which was about to be sent to the shops for repairs and new tubes, was set in the roundhouse and the boiler tested by the standard method. The locomotive was then sent to the shops and the boiler carefully cleaned and retubed. All the scale was removed and samples analyzed from nine different parts of the boiler. It was then sent back and again tested for evaporation under the same conditions as before cleaning. Before making the trials with the clean tubes the locomotive was allowed to make one or two trips on the road so as to insure its being thoroughly clean. The tests were made in the round-house at Champaign, Illinois.

The locomotive was set in the roundhouse over a pit and the tender removed. A car of coal was then run in back of the engine and on this were arranged the scales for weighing the coal. All of the feed water was weighed and then delivered into a tank placed on a platform by the side of the car, and connected with the suction pipe of the injector.

The slide valve on one side of the locomotive was moved back far enough, by disconnecting the valve rod, so that the steam generated could pass directly into the exhaust, and thus out through the nozzle and produce the necessary draft as usual. A 2-in. pipe was also run from the dome to the atmosphere, a valve in the pipe furnishing additional means of disposing of the steam generated. The tests were started by the standard method, i. e., raising steam to the running pressure, drawing the fire and starting with weighed wood.

At the end of the tests the ashes were all weighed. One of the regular road firemen fired for all the tests and the boiler and furnace were operated under the usual road conditions. A series of observations was made during these tests, to determine the re-

*This test constituted the thesis for graduation of Messrs. F. H. Armstrong and J. N. Herwig.

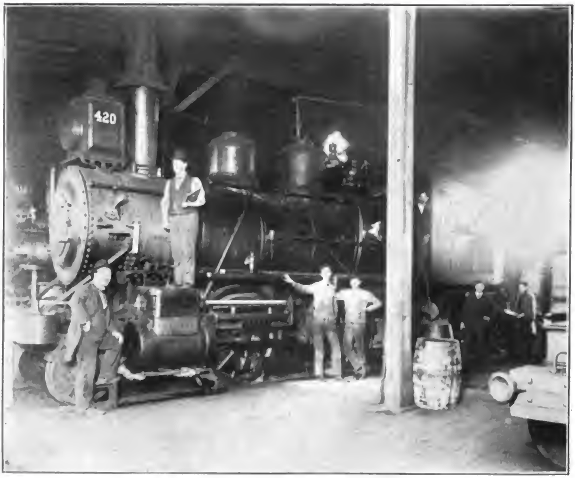

Fig. No. 1   Locomotive No. 420

lation between the blast-pipe pressures and vacuum in smoke box and furnace, as well as the velocity of the gases in the stack at various points along two diameters at right angles to each other. The locomotive upon which the tests were made was a Mogul freight engine made by the Rogers Locomotive Works, and was one of nineteen in use at that time on the Chicago division of the Illinois Central Railroad between Champaign and Centralia, Illinois. Fig. 1 shows the arrangements just described and gives a general view of the locomotive.

Leading dimensions:	
No. of Locomotive	420
Diameter of cylinder	19 in.
Stroke	26 in.
Diameter of drivers	56½ in.
Weight on drivers	106,400 lbs.
Weight on trucks	19,600 lbs.
Total weight of engine	126,000 lbs.
Diameter of boiler	62 in.
Number of tubes	236
Diameter of tubes	2 in.
Length of tubes	11 ft. 1 in. over tube sheets
Length of firebox	114⅛ in.
Width of firebox	33⅝ in.
Depth of firebox, front end	67⅞ in.
Depth of firebox, back end	59⅞ in.
Length of grate	114⅛ in.
Width of grate	33⅝ in.
Diameter of dry pipe	8 in. outside
Diameter of steam dome	29½ in. inside
Height of steam dome	28 in.
Kind of lagging	Magnesia sectional
Governing proportions:	
Grate area	26.45 sq. ft.
Total heating surface	1531.6 sq. ft.
Area of draft through tubes	573.5 sq. in.
Ratio of grate to heating surface	57.9
Fuel used:	
Commercial name	Odin
Commercial size	Mine run
Lumps per cent	75
Small coal per cent	20
Slack per cent	5
Heat units per lb. of dry coal (by calorimeter)	12,240

The results of these tests are exhibited in the accompanying tables.

TABLE 1

Log of Observations Giving Average Values

Locomotive No. 420 Illinois Central Railroad

	First Series Scale in Boiler		Second Series Cleaned Boiler	
Date of Trial (1898)	May 2	May 3	May 31	June 1
Duration of trial, hours	8.33	8.17	8.03	8.16
Steam pressure by gage	143	140	116.40	114
Vacuum in smoke box (in. of water)	2	2	2.9	2.8
Temperature of roundhouse (degrees F.)	72	62	79	89
Temperature of feed water in tank (degrees F.)	57	54	58.5	59.4
Temperature of escaping gases (degrees F.)	623	670	621	687
Temperature of steam (degrees F.)	362	360	348	346
Moisture in coal, per cent	4.0	4.0	4.0	4.0
Percentage of ash (from ash pan)	15.6	15.6	16.6	18.7
Percentage of moisture in steam	2.25	2.25	2.85	2.85

TABLE 2

Results of Evaporation Test of Locomotive Boiler
Engine No. 420, Illinois Central Railroad

First Series: After running 21 months and accumulating a scale deposit $\frac{1}{32}$ to $\frac{3}{64}$ inch thick.

Second Series: After cleaning and putting in new tubes.

		First Series Scale in Boiler			Second Series Clean Boiler		
	Date of Trial (1898)	May 2	May 3	Mean	May 31	June 1	Mean
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
Evaporative Performance	Water actually evaporated per lb. of dry coal	5.21	5.27	5.24	5.81	5.85	5.83
	Equivalent water from and at 212° F. per lb. of dry coal	6.29	6.39	6.34	6.99	7.04	7.01
	Water actually evaporated per lb. of combustible	6.17	6.25	6.21	6.95	7.16	7.05
	Equivalent water from and at 212° F. per lb. of combustible	7.46	7.59	7.53	8.36	8.61	8.48
Rate of Combustion	Dry coal burned per hour per sq. ft. of grate surface	57.45	58.51	57.95	59.80	60.00	59.90
	Per sq. ft. of tube opening	394.80	402.10	398.40	411.00	412.80	411.90
	Per sq. ft. of water heating surface	.93	.95	.94	.97	.98	.97
Rate of Evaporation	Water evaporated per hour from and at 212° F. per sq. ft. of grate surface	361.80	374.40	368.10	418.00	416.00	417.00
	Per sq. ft. of tube opening	2486.00	2573.00	2529.00	2874.00	2857.00	2865.00
	Per sq. ft. of water heating surface	5.89	6.09	5.99	6.81	6.76	6.79

The loss due to scale in this boiler was (7.01 minus 6.34) divided by 7.01 or 9.55 %.

The water used in the locomotive tested was taken from tanks at Centralia, Kinmundy, Little Effingham, Neoga, Dorans, Galton and Champaign. From the thickness of scale deposited during the 21 months it is evident that these waters are comparatively good for this section of the country.

The average thickness of the scale on the principal heating surfaces was $\frac{3}{64}$ in. The total weight of scale removed on cleaning was 485 lbs. The boiler had been in regular service during the 21 months.

The locomotive was cleaned and retubed at the Burnside shops of the Illinois Central Railroad. When the boiler was opened all the scale removed was carefully weighed, the scale on the tubes being determined by weighing the tubes before and after cleaning them. The scale from the shell and firebox sheets that could be removed was carefully collected. The total weight of scale was as follows:—

Weight of scale from flues..........................	360 lbs.
Weight of scale from shell..........................	125 lbs.
Total weight of scale..............................	485 lbs.

At nine different points in the boiler the thickness of the scale was determined by the average of many measurements, and samples were secured for analysis as follows:—

Point 1. Near injector discharge, hard and soft scale $\frac{1}{8}$ in. thick.
2. On upper tubes, hard smooth scale uniform thickness $\frac{1}{32}$ in.
3. On lower tubes, hard scale near middle, $\frac{1}{16}$ in. thick.
4. Mud covering hard scale at No. 3, $\frac{3}{32}$ in. thick.
5. Scale from side sheet, flue sheet, and tubes rough and scaly.
6. From bottom of barrel, 4 ft. from flue sheet.
7. On crown stays, 3 in. to 6 in. from crown sheet.
8. On crown sheet, rivet heads and base of stays.
9. From stay bolts at water line.

The results of the analyses of these scales calculated to compounds are shown in Table 3.

TABLE 3

RESULTS OF THE ANALYSES OF BOILER SCALE FROM ENGINE NO. 420

SCALE CONSTITUENTS CALCULATED TO COMPOUNDS AND EXPRESSED IN PER CENT

Point No.	Silica SiO_2	Iron and Aluminum Oxides Fe_2O_3 and Al_2O_3	Calcium Sulphate $CaSO_4$	Calcium Carbonate $CaCO_3$	Calcium Oxide CaO	Magesium Carbonate $MgCO_3$	Magnesium Oxide MgO	Organic Matter and Undetermined
1	7.70	3.20	10.86	65.81	....		9.55	2.78
2	25.20	7.10	16.45	20.92	....	3.05	19.52	7.67
3	8.00	4.99	21.22	48.90	1.90	....	4.48	10.51
4	7.84	3.27	4.38	61.17	....	8.14	5.47	9.73
5	15.89	4.30	21.38	30.36	....	8.71	7.66	11.70
6	11.25	7.70	1.97	67.08	....	....	9.29	2.71
7	18.25	6.90	1.95	45.51	5.69	....	16.77	4.93
8	13.05	7.85	40.03	24.33	1.14	....	9.12	4.48
9	22.70	12.75	11.73	28.32	....	5.86	18.45	0.11

The loss, as found by these trials, due to the presence of scale, was 9.55 % of the fuel.

EXPERIMENTS WITH SINGLE TUBES

The last three series of experiments to determine the loss due to scale have been laboratory experiments entirely. They were made during the years 1901, 1904 and 1905, and are referred to as the series of 1901, 1904 and 1905 respectively.*

The locomotive boiler tubes upon which the experiments were made in 1901 were furnished by the Peoria and Eastern division of the Cleveland, Cincinnati, Chicago and St. Louis, the Illinois Central, the Chicago, Burlington and Quincy, and the Chicago, Milwaukee and St. Paul Railways. The tubes used in 1904 and 1905 were furnished by the first two railroad companies mentioned above. Table No. 4 gives information concerning these tubes. Fig. 2 shows some of the tubes tested.

*These experiments were conducted by the following men as theses for graduation: Series of 1901, by F. L. McCune; Series of 1904, by W. A. Miskimen and C. N. Stone; Series of 1905, by H. F. Godeke and A. A. Hale.

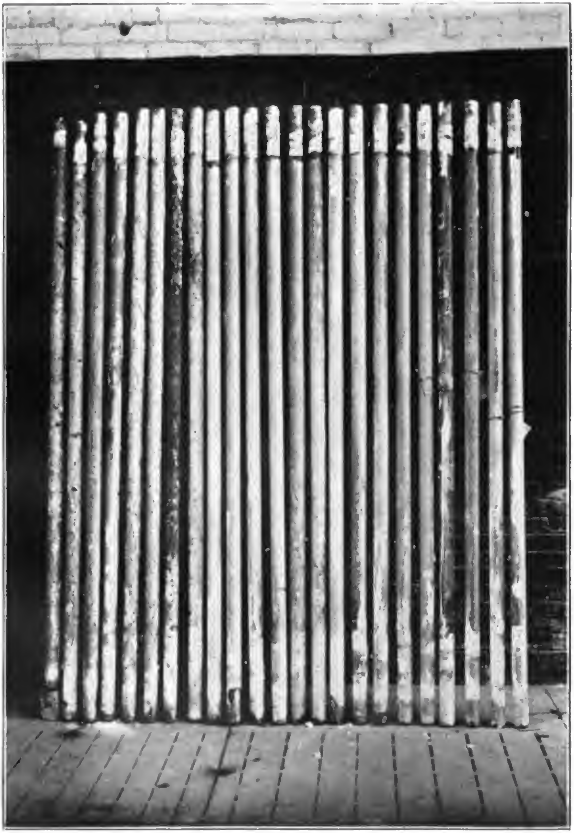

FIG. NO. 2 SCALED BOILER TUBES

TABLE 4

THE TRANSMISSION OF HEAT THROUGH SCALE-COVERED BOILER TUBES
RAILWAY ENGINEERING DEPARTMENT—UNIVERSITY OF ILLINOIS

Tube Number	Furnished by	No. of Engine from which Tube was taken	Length of time in service Months	Outside Diameter of Tube Inches	Average Thickness of Scale Inches	REMARKS General Character of Scale, Etc.
1	2	3	4	5	6	7
			SERIES OF 1901			
1	I. C. R. R.	311	10.5	2	0.06	Even, hard, dense
2	P. & E. RY.	526	13.5	2	0.04	Soft, porous. Removed in places
3	P. & E. RY.	536	5.5	2	0.02	Hard, dense, white
4	C. M. & ST. P.	126	....	2	0.03	Hard, dense, white
5	C. M. & ST. P.	1337	....	2	0.13	Hard, dense
6	I. C. R. R.	820	5.5	2	0.07	Mileage during service, 19690
7	P. & E. RY.	513	37.5	2	0.04	Hard, dense, rough, one end. Soft, porous at the other
9	C. B. & Q.	1179	....	2	0.11	Hard, porous, gray. Mileage, 50889
11	I. C. R. R.	1107	21	2	0.09	Soft, porous
14	P. & E. RY.	....	....	2	....	New and clean tube
			SERIES OF 1904			
1	I. C. R. R.	41	16	2	0.04	Hard, gray. In bad condition
2	I. C. R. R.	41	16	2	0.07	Loose, gray
3	I. C. R. R.	41	16	2	0.08	Loose, gray
4	I. C. R. R.	141	15	2	0.05	White, porous. Removed in places
5	I. C. R. R.	141	15	2	0.04	White, porous. Removed in places
6	I. C. R. R.	141	15	2	0.08	White, porous
7a	C.C.C. & ST. L.	540	..	2	0.06	White, soft, irregular
7b	C.C.C. & ST. L.	540	..	2	0.06	White, soft, irregular
8a	C.C.C. & ST. L.	540	..	2	0.05	Hard, white, irregular
8b	C.C.C. & ST. L.	540	..	2	0.04	Hard, white
9	I. C. R. R.		..	2	0.06	Hard
10	I. C. R. R.	440	..	2	0.03	Hard, gray
11	I. C. R. R.	440	..	2	0.09	Gray, porous
12	I. C. R. R.	440	..	2	0.03	Gray, porous
13	I. C. R. R.	...	..	2	....	Clean tube
			SERIES OF 1905			
3	I. C. R. R.	136	18	2	0.07	Medium
4	I. C. R. R.	802	8	2	0.05	Hard
8	C.C.C. & ST. L.	533	10	2	0.03	Soft
9	C.C.C. & ST. L.	233	14	2	0.09	Very soft
10	I. C. R. R.	1424	10	2	0.07	Soft
11	C.C.C. & ST. L.	233	14	2	0.04	Very soft
12	I. C. R. R.	140	21	2	0.07	Hard
13	I. C. R. R.	303	18	2	0.02	Hard
14	I. C. R. R.	1004	21	2	0.04	Medium
15	I. C. R. R.	1012	12	2	0.03	Very hard
7	....	....	..	2	....	Clean tube

These tests were made as laboratory tests on account of the desire to make comparative tests under entirely similar conditions except in regard to the scale itself and in order that more exact measurements might be made than were found possible with road or roundhouse tests. The apparatus used in all of these tests has been practically the same from year to year. It is shown in Fig. 3, 4, and 5 and consists of a long water chamber through which the tube to be tested was passed, and in which water was circulated. On one end of this water chamber was fastened a combustion chamber, at the forward end of which was placed a burner. This burner was supplied with gas and air. Combustion took place in the chamber, which served the purpose of the firebox. The hot gases passed through the boiler tube to the air. The water entered the water chamber at the right, leaving it at the left as indicated in Fig. 3, at both of which points its temperature was read upon the thermometers there shown. The water tank received the water from the city mains. It was provided with an overflow, as shown, and the water was led directly down from the bottom of this tank to the water chamber. This was used in order to give a constant pressure at the inlet and thus to avoid variations in the rate of flow of the water. The gas and air tanks were arranged to give constant pressures of gas and air. The inner vessels, open at the bottom, float in water contained in the outer tank and confine the air or gas in the space above the water level. These inner tanks can be weighted at will to give any desired pressure to the air or gas contained within them.

During the tests of 1901 a copper ball pyrometer was employed to obtain the temperatures of the gases entering the tube being tested. For the series of 1904 and 1905 a Le Chatelier pyrometer was employed for this purpose. The location of the pyrometer is shown in Fig. 3. The temperature of the gases as they left the flue was read on the thermometer shown at the end of the tube.

The purpose of the tests was to measure the number of heat units transmitted per hour through the different tubes. This was accomplished by weighing the water which circulated around the tube in the water chamber and measuring its rise in temperature. The attempt was made to maintain a constant furnace temperature at the entrance to the tubes throughout all experiments of each

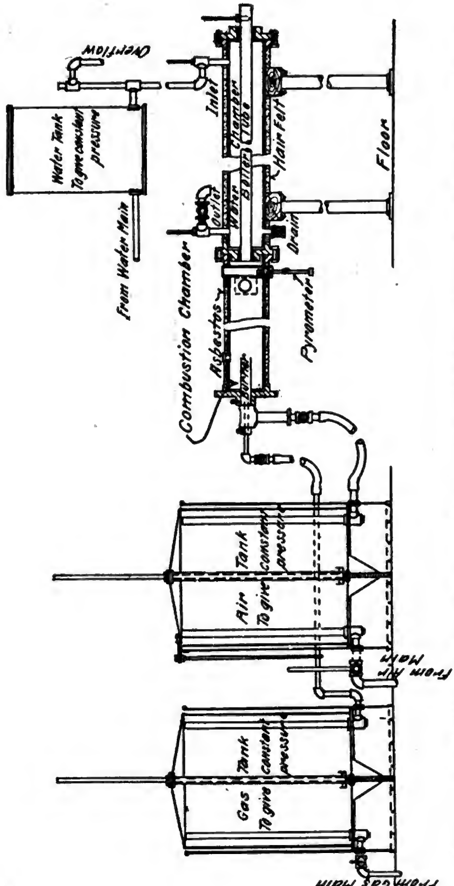

FIG. No. 3 APPARATUS FOR THE DETERMINATION OF THE EFFECT OF SCALE ON HEAT TRANSMISSION THROUGH TUBES

series and thereby have available for transmission the same amount of heat, since the amounts of gas and air supplied to the burner were continually the same.

TABLE 5

THE TRANSMISSION OF HEAT THROUGH SCALE-COVERED BOILER TUBES

RAILWAY ENGINEERING DEPARTMENT—UNIVERSITY OF ILLINOIS

Tube Number	Test Number	Duration of Test—Hours	Average Temperatures During Tests Degrees Fahr. — Of Furnace Gases — In Combustion Chamber	Of Furnace Gases — Of Escaping Gases	Of Furnace Gases — Average Temperature of Gases	Of Circulating Water — At The Inlet	Of Circulating Water — At The Outlet	Of Circulating Water — Average Temperature of Water	Of Circulating Water — Rise in Temperature of Water	Weight of Water Used During Test—In Pounds	Difference Between Temperature of Water and Temperature of Gases—"Range of Temperature"—Column 6 Minus Column 9	B. T. U. Transmitted Through Tube During Test	B. T. U. Which Would Have Been Transmitted Had The Range Of Temperature Been The Same As For Clean Tubes	Decrease in Conductivity Due to Scale Per Cent Loss
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SERIES OF 1901														
1	11	1	1657	256	957	66.9	112.7	89.8	45.8	651.3	867.2	29830	30063	*0.6
1	12	1	1702	252	977	66.8	112.6	89.7	45.8	643.3	887.3	29463	29021	2.9
2	16	1	1650	260	955	65.0	113.9	89.5	48.9	526.5	865.5	25746	25999	13.0
2	18	1	1631	269	950	64.1	110.3	87.2	46.2	584.0	862.8	26981	27331	8.5
3	1	1	1693	239	966	64.7	110.4	87.6	45.7	593.5	878.4	27123	26987	9.7
3	2	1	1690	238	964	65.7	111.0	88.4	45.3	600.7	875.6	27212	27162	9.1
4	20	1	1639	259	949	67.1	111.2	89.2	44.1	676.0	859.8	29812	30304	*1.4
4	21	1	1622	252	937	66.8	109.7	88.3	42.9	713.5	848.7	30609	31522	*5.5
5	6	1	1559	248	904	65.9	110.6	88.3	44.7	583.0	815.7	26060	27923	6.5
5	22	1	1702	265	984	63.9	109.3	87.1	45.4	624.0	896.9	28330	27606	7.6
6	3	1	1682	265	974	65.3	110.4	87.9	45.1	685.5	886.1	30916	30494	*2.1
6	23	1	1718	284	1001	63.6	110.7	87.2	47.1	646.0	913.8	30427	29101	2.6
7	8	1	1695	252	974	67.1	113.3	90.2	46.2	612.0	883.8	28274	27961	6.4
7	9	1	1693	256	975	66.9	112.0	89.5	45.1	669.5	885.5	30194	29802	0.2
9	4	1	1535	249	892	65.3	109.9	87.6	44.6	546.0	804.4	24351	26459	11.4
9	15	1	1597	252	925	65.8	110.9	88.4	45.1	505.0	836.6	22776	23794	20.4
11	7	1	1659	262	961	63.9	110.0	87.0	46.1	589.3	874.0	27167	27167	9.1
11	24	1	1683	271	977	64.1	109.5	86.8	45.4	590.5	890.2	26809	26321	11.9
14	5	1	1595	266	931	64.0	109.4	86.7	45.4	644.0	844.3	29238	Clean	
14	13	1	1690	267	979	67.8	114.0	90.9	46.2	650.2	888.1	30039	Tubes	
14	14	1	1693	268	981	68.5	114.2	91.4	45.7	664.0	889.6	30345	*Increase	
Average			1659	267	964	66.8	112.5	89.7	45.8	652.7	874.0	29874		

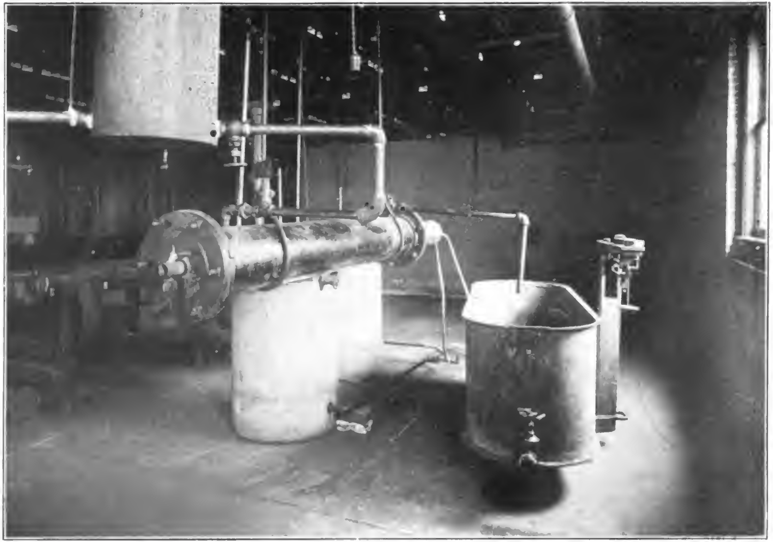

Fig. No. 4 Apparatus for the Determination of the Effect of Scale on Heat Transmission Through Tubes

FIG. NO. 5 APPARATUS FOR THE DETERMINATION OF THE EFFECT OF SCALE ON HEAT TRANSMISSION THROUGH TUBES

Series of 1904

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	15	1	1432	648	1040	56.8	84.7	70.8	27.9	829	969.2	23129	22227	5.1
2	16	1	1439	659	1049	57.9	84.0	71.0	26.1	850	978.0	22185	21128	9.8
3	17	1	1436	667	1052	58.0	83.2	70.6	25.2	895	981.4	22554	21405	8.6
4	18	1	1418	515	967	57.7	80.4	69.1	22.7	975	897.9	22183	22958	2.0
5	19	1	1438	523	981	57.1	83.4	70.3	26.3	814	910.7	21408	21895	6.5
6	20	1	1439	511	975	58.3	82.7	70.5	24.4	865	904.5	21106	21734	7.2
7a	13	1	1439	647	1043	57.0	81.9	69.5	24.9	875	973.5	21788	20845	11.0
7b	14	1	1437	523	980.	56.5	81.5	69.0	25.0	803	911.0	20075	20525	12.4
8a	12	1	1443	623	1033	57.0	89.4	73.2	32.4	662	959.8	21449	20812	11.1
8b	11	1	1414	593	1004	58.9	91.3	75.1	32.4	654	928.9	21190	21247	9.3
9	10	1	1423	547	985	57.6	83.8	70.7	26.2	767	914.3	20095	20471	12.6
10	7	1	1431	517	974	59.1	84.8	72.0	25.7	808	902.0	20766	21442	8.5
11	8	1	1415	536	976	58.8	85.1	72.0	26.3	735	904.0	19831	19916	15.0
12	9	1	1426	551	989	59.0	82.9	71.0	23.9	896	918.0	21414	21727	7.2
13a	6	1	1441	554	998	56.5	82.5	69.5	26.0	891.	928.5	23166	Clean Tubes	
13b	5	1	1439	563	1001	56.7	85.1	70.9	28.4	825.	930.1	23430		
13c	4	1	1440	569	1005	56.3	82.6	69.5	26.3	900.	935.5	23670		
Average			1440	563	1001	56.5	83.4	70.0	26.9	872.	931.4	23422		

Series of 1905

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3	48	1	1783	873	1328	62.4	103.6	83.0	41.2	717	1245.0	29540	28722	2.8
3	49	1	1781	879	1330	62.4	102.1	82.3	39.7	753	1247.7	29894	29002	1.9
3	50	1	1798	867	1333	62.0	99.2	80.6	37.2	800	1252.4	29760	28764	2.7
4	45	1	1816	733	1275	62.2	102.6	82.4	40.4	699	1192.6	28240	28663	3.0
4	46	1	1809	715	1262	63.2	102.0	82.6	38.8	707	1179.4	27432	28155	4.8
4	47	1	1806	705	1256	63.3	102.4	82.9	39.1	692	1173.1	27057	27920	5.6
8	24	1	1788	740	1264	59.7	102.7	81.7	43.0	641	1182.3	27563	28220	4.5
8	25	1	1790	743	1267	60.1	102.4	81.3	42.3	660	1185.7	27918	28502	3.6
8	26	1	1805	743	1274	60.1	101.7	80.9	41.6	656	1193.1	27290	27688	6.3
9	27	1	1752	791	1272	59.9	101.1	80.5	41.2	683	1191.5	28140	28588	3.3
9	28	1	1753	800	1277	60.0	100.6	80.3	40.6	682	1196.7	27690	28009	5.2
9	29	1	1763	793	1278	59.7	100.6	80.2	40.9	695	1197.8	28426	28727	2.8
10	30	1	1772	786	1279	59.0	101.2	80.1	42.2	674	1198.9	28443	28718	2.9
10	31	1	1782	788	1285	58.8	101.8	80.3	43.0	663	1204.7	28509	28646	3.1
10	32	1	1783	792	1288	59.1	101.4	80.3	42.3	671	1207.7	28383	28449	3.8
11	34	1	1776	805	1291	67.1	103.1	85.1	36.0	767	1205.9	27612	27717	6.2
11	35	1	1785	803	1294	67.0	102.4	84.7	35.4	753	1209.7	26656	26674	9.8
12	37	1	1776	804	1290	64.5	102.1	83.3	37.6	747	1206.7	28087	28176	4.7
12	38	1	1785	790	1288	64.0	102.1	83.1	38.1	721	1204.9	27470	27598	6.6
13	39	1	1766	740	1253	60.2	101.4	80.8	41.2	679	1172.2	27975	28889	2.3
13	40	1	1754	748	1251	60.7	102.9	81.8	42.2	668	1169.2	28190	29190	1.3
13	41	1	1747	736	1242	61.2	101.5	81.4	40.3	695	1160.6	28009	29213	1.2
14	43	1	1805	808	1307	58.5	102.1	80.3	43.6	657	1226.7	28645	28267	4.4
14	44	1	1792	803	1298	58.8	102.9	80.9	44.1	645	1217.1	28445	28290	4.3
15	51	1	1804	759	1282	61.1	102.1	81.6	41.0	688	1200.4	28208	28445	3.8
15	52	1	1808	736	1272	60.8	100.9	80.9	40.1	701	1191.1	28110	28568	3.4
7	21	1	1792	794	1293	64.5	102.1	83.3	37.6	782	1209.7	29403	Clean Tubes	
7	22	1	1796	787	1292	64.2	103.6	83.9	39.4	754	1208.1	29708		
7	23	1	1808	784	1296	63.3	101.4	82.4	38.1	776	1213.6	29566		
Average			1799	788	1294	64.0	102.4	83.2	38.4	770.7	1210.5	29559		

The method of conducting a test was as follows:

The burner was first lighted and the gas and air pressures adjusted, then the flow of water through the water chamber was regulated and the apparatus allowed to run until all conditions had become uniform. This usually occupied about one hour, at the end of which time the test was started.

At the beginning of a test for the series of 1901 a determination of temperature was made by the copper ball pyrometer and readings were taken on all three thermometers, which readings were also taken at intervals of five minutes throughout the test. At the end another determination was made of the furnace temperature, and the water which had flowed through the chamber was weighed.

Observations for the tests of 1904 and 1905 were taken in a similar manner except that all temperature readings including that of the furnace were taken at regular intervals of 10 minutes.

Table No. 5 gives a summary of the data of the various tests and also the calculated results. The furnace temperature was not maintained quite the same throughout the tests, as an inspection of Table No. 5 will show. It was likewise impossible to maintain the average temperature of the circulating water the same during all the tests. Consequently the range of temperature between the gases in the tube and the water varied somewhat. Since the rate of transmission of heat through the tube varies directly with this range in temperature it is necessary, in order to compare the conductivity of the different tubes, to reduce the actual amounts of heat transmitted to what they would have been for one standard range of temperature. This standard range was assumed the same as the range existing during the test of a new clean tube, such a tube being tested with each series of tests.

These derived figures are given in column 14, Table No. 5, and they show the amounts of heat which would have been transmitted in each case had the difference between the temperature of the gases and the temperature of the water been the same in all tests of that particular series, i. e., the same as during the tests of the clean tube then tested. It is from the figures in this column that the losses due to scale are computed. This loss expressed as a per cent is exhibited in column 15 of Table No. 5.

Table No. 6 gives the chemical analyses of the scale found upon the tubes tested in the series of 1901, 1904 and 1905. The constituents of the scale are calculated to compounds and expressed as per cent. These analyses were made by the Chemical department of the University of Illinois.

TABLE 6

The Transmission of Heat through Scale-covered Boiler Tubes
Railway Engineering Department—University of Illinois

CHEMICAL ANALYSES OF SCALE

Constituents of Scale — Amount in per cent

Tube Number	SiO_2 Silica	Fe_2O_3 Al_2O_3 Oxides of Iron and Aluminum	$CaSO_4$ Calcium Sulphate	$CaCO_3$ Calcium Carbonate	CaO Calcium Oxide	$MgCO_3$ Magnesium Carbonate	MgO Magnesium Oxide	Moisture	Organic Matter and Alkali
1	2	3	4	5	6	7	8	9	10
Series of 1901									
1	7.00	8.32	16.78	47.16	....	1.30	11.20	1.18	7.06
2	5.68	8.98	27.30	22.27	10.45	....	15.82	1.14	8.34
3	9.24	10.98	2.04	59.75	0.62	....	10.18	0.64	6.55
4	9.80	15.92	25.86	23.20	3.02	....	13.16	1.42	7.62
5	10.00	7.00	14.35	50.30	....	8.40	7.30	0.84	1.81
6	7.42	4.26	16.08	51.44	....	1.53	11.25	1.19	6.83
7	12.22	5.38	17.70	37.02	....	0.79	16.76	1.63	8.50
9	12.46	11.24	36.85	21.37	....	3.13	0.72	1.02	13.21
11	17.82	10.32	5.06	37.50	6.70	....	13.92	2.25	6.43
Series of 1904									
1	26.04	10.80	1.36	27.50	3.84	.....	23.07	7.39	
2	17.21	8.02	18.50	11.52	....	15.61	21.74	7.40	
3	15.10	3.95	21.93	10.48	....	11.06	25.28	12.20	
4	8.99	1.90	22.81	49.11	....	14.11	0.50	2.58	
5	9.11	2.20	47.96	16.85	....	2.46	11.76	9.66	
6	12.10	2.60	54.99	10.78	....	4.63	9.57	5.33	
7a	12.93	1.35	21.83	31.14	....	5.14	15.94	11.67	
7b	12.93	1.35	21.83	31.14	....	5.14	15.94	11.67	
8a	12.70	2.33	35.05	17.03	....	3.99	17.85	11.05	
8b	12.70	2.33	35.05	17.03	....	3.99	17.85	11.05	
9	23.52	7.20	6.56	37.56	3.48	.....	5.59	16.09	
10	10.05	6.47	11.71	50.98	....	7.33	4.94	8.52	
11	9.75	2.08	6.05	54.71	....	5.72	6.43	15.26	
12	7.98	4.68	8.89	55.61	....	11.36	3.75	7.73	
Series of 1905									
3	7.09	5.05	17.16	19.45	.....	0.77	34.10	0.58	15.80
4	6.92	3.57	21.57	3.61	25.61	....	1.85	0.56	36.31
8	6.61	1.34	0.62	74.26	.....	0.15	10.87	0.68	5.47
9	8.44	2.52	12.59	56.80	.....	0.33	11.43	0.87	7.02
10	3.33	1.43	5.82	67.99	1.64	....	11.11	0.48	8.20
11	7.09	2.30	14.87	58.18	.....	2.22	8.26	0.75	6.33
12	27.72	9.53	12.11	10.05	0.24	....	29.90	1.07	9.38
13	9.54	10.38	8.41	9.67	3.87	....	39.09	0.71	18.33
14	16.87	4.73	2.22	40.30	6.06	....	19.25	0.83	9.74
15	24.08	12.69	1.46	31.37	0.35	....	20.91	1.45	7.74

Table No. 7 gives a summary of the data and results. In it are given for each tube the corresponding average loss as determined by the several experiments, as well as the thickness and some of the results of analyses. From this table there have been plotted five diagrams—Fig. 6, 7, 8, 9 and 10, which exhibit the loss due to the scale with reference to thickness, hardness and chemical composition. Fig. 6 shows the loss due to scale plotted with reference to its thickness. Fig. 7 is identical with Fig. 6, except that the letters H, S or M have been added at the various points to indicate the scale as being either hard, soft, or medium. In Fig. 8, 9 and 10 the loss due to the scale is plotted with reference to the amount of its chemical constituents; in Fig. 8 with reference to the sum of the percentages of calcium carbonate and magnesium carbonate; in Fig. 9 with reference to the percentage of calcium sulphate; and in Fig. 10 with reference to the percentage of silica.

In the series of 1901 there are a few tests which indicate an increase of conductivity of the scaled tube as compared with the clean tube. These are perhaps to be accounted for by errors in conducting the experiments, although they could not be detected at the time the experiments were made. The apparatus used in 1904 and 1905 was improved in some particulars, the most important change being in the means for the measurement of furnace temperatures. Such discrepancies disappear in the latter series.

When the experiments were planned it was considered probable that the transmission of heat through the scale was principally dependent upon two of its characteristics, namely, its thickness and its mechanical structure and that probably, for such thicknesses as are usually met with, thickness had greater influence than structure. Thickness was therefore carefully determined and structure approximately designated as in Table 4, as hard, soft or medium, no more exact characterization of structure being possible with tubes collected from different sources as these were.

It was hoped that the experiments might develop, if perhaps only approximately, some law of variation of conductivity with thickness. After making allowance for probable errors due to the method of conducting the tests, consideration of Fig. 6 shows perhaps a decrease of conductivity with thickness; but certainly no regularity of variation. In Fig. 7 the loss in heat transmission is again plotted with reference to thickness; and the structure of the scale, in so far as it was determined, is indicated as previously explained. No regularity of variation is observable with respect to hardness or softness.

TABLE 7

SUMMARY

THE TRANSMISSION OF HEAT THROUGH SCALE-COVERED BOILER TUBES

RAILWAY ENGINEERING DEPARTMENT—UNIVERSITY OF ILLINOIS

SERIES OF 1901

Tube No.	Test No.	Loss per cent	Ave. Loss per cent	Character of Scale	Thickness of Scale	$CaCO_3+MgCO_3$ in Scale	$CaSO_4$ in Scale	SiO_2 in Scale
1	11	*0.6	1.2	H	0.06	48.46	16.78	7.00
1	12	2.9						
2	16	13.0	10.8	S	0.06	22.27	27.30	5.68
2	18	8.5						
3	1	9.7	9.4	H	0.02	59.75	2.04	9.24
3	2	9.1						
4	20	*1.4	*3.5	H	0.03	23.20	25.86	9.80
4	21	*5.5						
5	6	6.5	7.1	H	0.13	58.70	14.35	10.00
5	22	7.6						
6	3	*2.1	0.3	✓	0.07	52.97	16.08	7.42
6	23	2.6						
7	8	6.4	3.3	M	0.01	37.81	17.70	12.22
7	9	0.2						
9	4	11.4	15.9	H	0.11	24.50	36.85	12.46
9	15	20.4						
11	7	9.1	*0.5	S	0.09	37.50	5.06	17.82
11	24	11.9						

*Increase

SERIES OF 1904

Tube No.	Test No.	Loss per cent	Ave. Loss per cent	Character of Scale	Thickness of Scale	$CaCO_3+MgCO_3$ in Scale	$CaSO_4$ in Scale	SiO_2 in Scale
1	15	5.1	....	H	0.04	27.50	1.36	26.04
2	16	9.8	....	S	0.07	27.13	18.50	17.21
3	17	8.6	....	S	0.08	21.54	21.93	15.10
4	18	2.0	....	S	0.05	63.22	22.81	8.99
5	19	6.5	....	S	0.04	19.31	47.96	9.11
6	20	7.2	....	S	0.08	15.41	54.99	12.10
7a	13	11.0	....	S	0.06	36.28	21.83	12.93
7b	14	12.4	....	S	0.06	36.28	21.83	12.93
8a	12	11.1	....	H	0.05	21.02	35.05	12.70
8b	11	9.3	....	H	0.04	21.02	35.05	12.70
9	10	12.6	....	H	0.06	37.56	6.56	23.52
10	7	8.5	....	H	0.03	58.31	11.71	10.05
11	8	15.0	....	S	0.09	60.43	6.05	9.75
12	9	7.2	....	S	0.03	66.97	8.89	7.98

SERIES OF 1905

Tube No.	Test No.	Loss per cent	Ave. Loss per cent	Character of Scale	Thickness of Scale	$CaCO_3+MgCO_3$ in Scale	$CaSO_4$ in Scale	SiO_2 in Scale
3	48	2.8	2.5	M	0.07	20.22	17.16	7.09
3	49	1.9						
3	50	2.7						
4	45	3.0	4.5	H	0.05	3.61	21.57	6.92
4	46	4.8						
4	47	5.6						
8	24	4.5	4.8	S	0.03	74.41	0.62	6.61
8	25	3.6						
8	26	6.3						
9	27	3.3	3.8	S	0.09	57.13	12.59	8.44
9	28	5.2						
9	29	2.8						
10	30	2.9	3.3	S	0.07	67.99	5.82	3.33
10	31	3.1						
10	32	3.8						
11	34	6.2	8.0	S	0.04	60.40	14.87	7.09
11	35	9.8						
12	37	4.7	5.7	H	0.07	10.05	12.11	27.72
12	38	6.6						
13	39	2.3	1.6	H	0.02	9.67	8.41	9.54
13	40	1.3						
13	41	1.2						
14	43	4.4	4.4	M	0.04	40.30	2.22	16.87
14	44	4.3						
15	51	3.8	3.6	H	0.03	31.37	1.46	24.30
15	52	3.4						

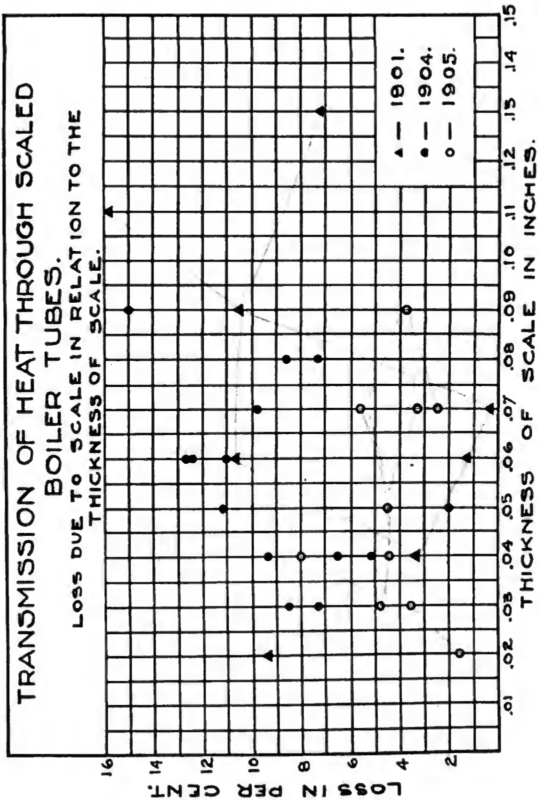
TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE THICKNESS OF SCALE.
▲ — 1901.
● — 1904.
○ — 1905.
THICKNESS OF SCALE IN INCHES.
.01 .02 .03 .04 .05 .06 .07 .08 .09 .10 .11 .12 .13 .14 .15
LOSS IN PER CENT.
2 4 6 8 10 12 14 16

Fig. 6

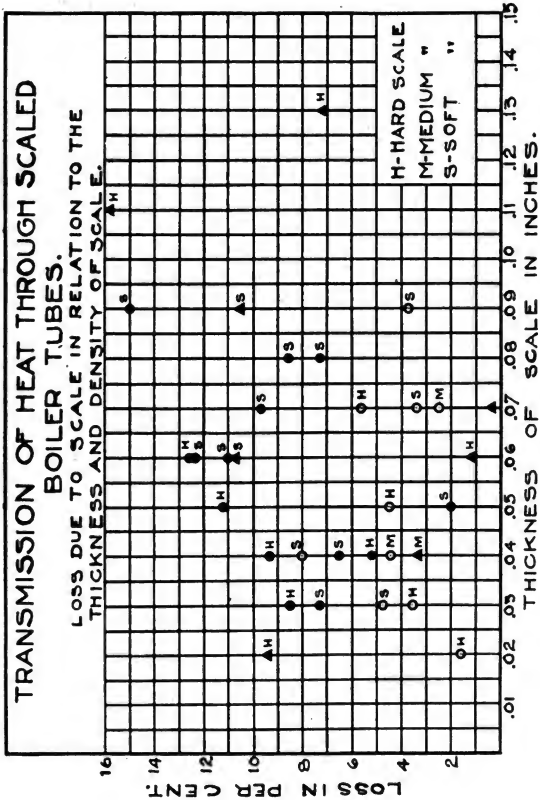
TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE THICKNESS AND DENSITY OF SCALE.
H-HARD SCALE
M-MEDIUM "
S-SOFT "
LOSS IN PER CENT.
16
14
12
10
8
6
4
2
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
.15
THICKNESS OF SCALE IN INCHES.

Fig. 7

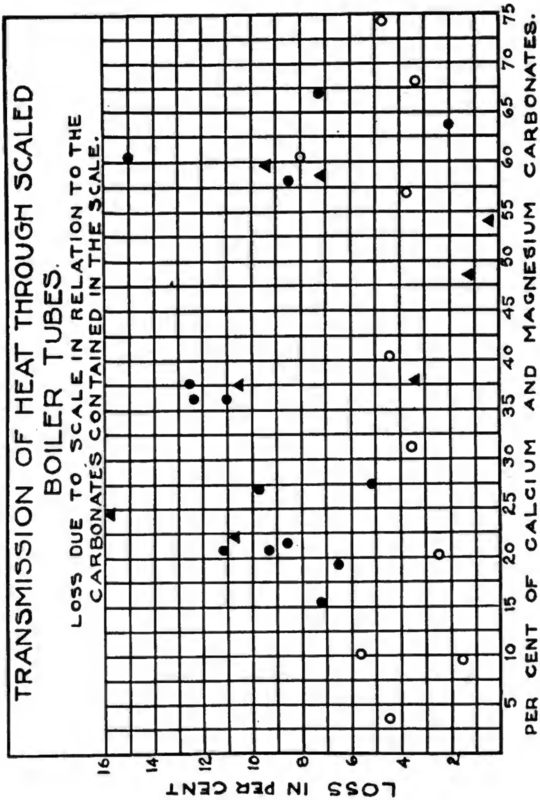
TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE CARBONATES CONTAINED IN THE SCALE.
16 14 12 10 8 6 4 2
LOSS IN PER CENT
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
PER CENT OF CALCIUM AND MAGNESIUM CARBONATES.

FIG. 8

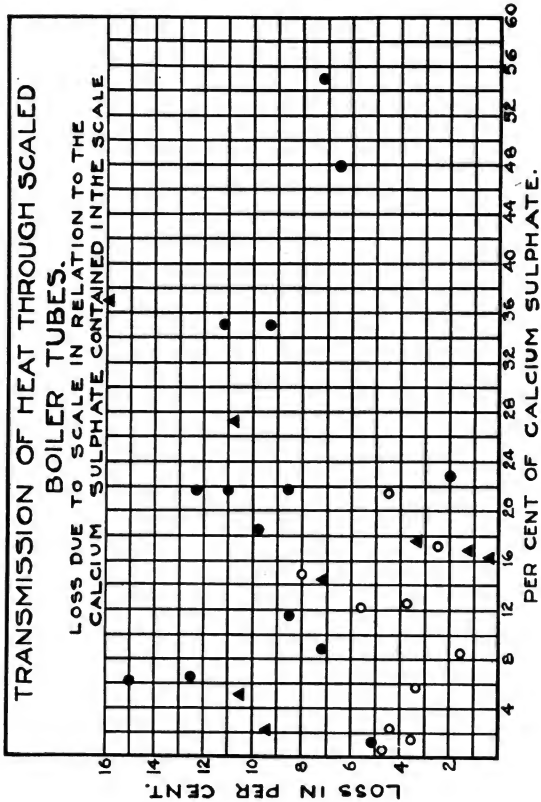
TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE CALCIUM SULPHATE CONTAINED INTHE SCALE
4 8 12 16 20 24 28 32 36 40 44 48 52 56 60
PER CENT OF CALCIUM SULPHATE.
16 14 12 10 8 6 4 2
LOSS IN PER CENT.

Fig. 9

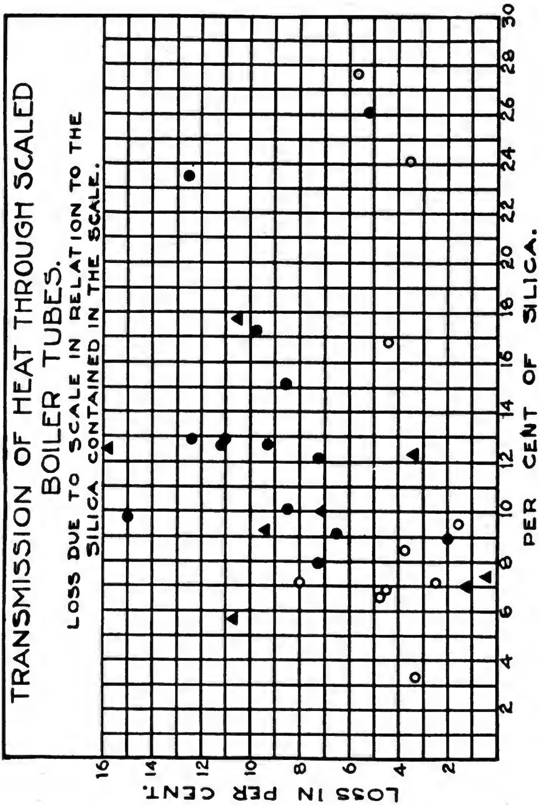
TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE SILICA CONTAINED IN THE SCALE.
LOSS IN PER CENT.
PER CENT OF SILICA.
16
14
12
10
8
6
4
2
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

Fig. 10

In considering Fig. 6 and 7 it must be borne in mind that the tubes tested were taken from locomotives which had been in service in different parts of the country and that the scale on each tube was made up of the mineral constituents of many different water supplies. What is designated as hard scale in one case may be very different in structure—in porosity, for example—from what is designated as hard scale on another tube. Fig. 7 cannot therefore be considered as providing conclusive evidence concerning variation of conductivity with structure. The results may properly be interpreted as indicating that mechanical structure is at least as important a factor in the change in heat transmission due to scale as is the mere thickness. Such a conclusion is, of course, in accord with the facts concerning other heat insulators.

Fig. 8, 9 and 10, in which the loss in heat transmission is plotted with reference to the principal chemical constituents of the scale, do not warrant the conclusion that its chemical composition has any direct influence on its conductivity.

From the point of view of the physicist the experiments are open to objection as to method. From the engineer's viewpoint it is believed that the possible errors of the experiments do not, by any means, account for all the irregularity in the plotted results, and considering the controversy upon this subject and the comparatively meager information available, it is deemed proper to publish at this time the results as they stand in the hope that they contribute additional information which may be of interest in some quarters.

Conclusions:

In so far as generalization is warranted we may sum up the results of the tests in the following conclusions:

1. Considering scale of ordinary thickness, say of thicknesses varying up to ⅛ inch, the loss in heat transmission due to scale may vary in individual cases from insignificant amounts to as much as 10 or 12 per cent.

2. The loss increases somewhat with the thickness of the scale.

3. The mechanical structure of the scale is of as much or more importance than the thickness in producing this loss.

4. Chemical composition, except in so far as it affects the structure of the scale, has no direct influence on its heat transmitting qualities.

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